A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR-84-2114

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE RIO GRANDE RIFT: PROBLEMS AND PERSPECTIVES

LA-UR--84-2114

DE84 015492

AUTHOR(S) W. Scott Baldridge, Kenneth H. Olsen, and Jonathan F. Callender*

SUBMITTED TO New Mexico Geological Society Guidebook, 35th Annual Conference
October 10-13, 1984
Taos, New Mexico

*New Mexico Museum of Natural History
Albuquerque, New Mexico

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

RIO GRANDE RIFT: PROBLEMS AND PERSPECTIVES

W. SCOTT BALDRIDGE and KENNETH H. OLSEN
Earth and Space Sciences Division
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

and

JONATHAN F. CALLENDER
New Mexico Museum of Natural History
Albuquerque, New Mexico 87194

INTRODUCTION

Our intent in this paper is, first, to present new ideas concerning the Rio Grande rift which we hope are at least provocative if not correct. Second, we would like to emphasize what we think to be important unanswered questions which will be fruitful areas for continued research. Our approach is to evaluate, relate, and interpret existing data derived from a number of disciplines, rather than primarily to present new data. In taking this approach we hope to achieve a synthesis of sorts — a new and broad perspective on the Rio Grande rift. This perspective should help guide future observations by directing our attention toward the more fundamental questions regarding rifting processes. In this paper we accept the Basaltic Volcanism Study Project's (1981, p. 838) definition of rifts as elongate depressions overlying places where the entire thickness of the lithosphere has ruptered in extension.

Among the topics and ideas that we address are: (1) the regional extent of the Rio Grande rift, (2) the structure of the crust and upper mantle, (3) whether the evidence for an "axial dike" (i.e., a composite mafic intrusion in the lower crust, as is typically assumed or inferred for continental rifts, is compelling, (4) the nature of faulting and extension in the crust, and (5) the structural and magmatic development of the rift. These

issues provide important constraints on the nature of thermal and tectonic processes involved in formation of the Rio Grande rift.

The Rio Grande rift is a region where the lithosphere is being permanently altered through thinning and (probably less importantly) through intrusion of mafic magmas. The rift is the culmination of a long and complex geologic history. Initiation of rifting probably resulted from plate boundary interactions along the west coast of North America. However, the presence of a major thermal event associated with the immediately preceding subduction regime may have been a necessary condition for rifting.

DESCRIPTION AND REGIONAL EXTENT

The Rio Grande rift extends as a well-defined series of asymmetrical grabens from Leadville, Colorado, to Presidio, Texas, and Chihuahua, Mexico, a distance of more than 1000 km (fig. 1). North of Socorro the rift is a distinctive morpho-tectonic feature. The main rift grabens have undergone vertical structural offsets of as much as 6 km (e.g., near Bernalillo). South of Socorro the rift is not physiographically distinctive, yet can be distinguished from the adjacent Basin and Range province by a variety of geologic and geophysical signatures (Seager and Morgan, 1979).

Over much of its length the rift is part of a broad region of "rift-like" late Cenozoic extensional deformation, i.e., a region characterized by large crustal blocks separated by steeply dipping normal faults. In central New Mexico, west of Albuquerque and Socorro, this region is over 200 km in width, extending southwestward across the physiographic Colorado Plateau to Springerville, Arizona, and perhaps farther (Baldridge and others, 1983). A broadly linear, northeast-trending array of late Cenozoic volcanic fields, commonly referred to as the Jemez lineament, separates this extended terrain

(transition zone) along the southeastern margin of the Plateau from the less deformed "core" to the northwest. The Jemez lineament must correspond to a major boundary or zone of weakness in the lithosphere. However, it is not an expression of a fault or fracture zone and does not correspond to any single, simple structure in the upper crust (Baldridge and others, 1983). Farther south, the extended region encompasses the entire Mogollon-Datil volcanic field. In southern New Mexico and northern Chihuahua, the rift is not physiographically distinguishable from the Basin and Range province, extending across southern Arizona and southern New Mexico.

Although the style and timing of structural deformation of the entire extended region are similar to that of the main rift grabens (i.e., extensional deformation), the magnitude of deformation is much less. Vertical offset on normal faults of the Colorado Plateau transition zone probably do not exceed a few hundred meters. In the Mogollon-Datil region of southwestern New Mexico, narrow, deep grabens exist near Datil, Reserve, and Silver City, but these are separated from the larger, main grabens of the rift by a region a hundred kilometers or so wide in which extensional deformation formed only shallow grabens.

The recognition of a broad, "rift-like" region is fully in accord with definitions of the rift based on geophysical and topographic criteria (e.g., Cordell, 1978; Ander, 1981). Whether the term "Rio Grande rift" is applied to the entire region (e.g., Cordell, 1978), or is restricted to the deeper, physiographically-distinguishable main grabens, as we prefer, is largely a semantic argument. The important point is that the continuity of structural style and timing across this broad region clearly indicate a continuity in underlying processes. That is, formation of the Rio Grande rift and Colorado Plateau transition zone and breakup of the Mogollon-Datil volcanic field all

resulted from, and were part of, the very widespread Basin and Range deformational event.

LITHOSPHERIC STRUCTURE

The fact that deformation associated with the Rio Grande rift affected such a large region indicates that it resulted from an event that perturbed the entire lithosphere. The structure of the lithosphere beneath the rift is anomalous in many respects (fig. 2):

(1) A moderate amount of crustal thinning has taken place beneath the axis of the rift. Seismic refraction profiles show that at the latitude of Figure 2, depth to Moho is 33 km beneath the Albuquerque-Belen basin compared to about 45 km under the Arizona-New Mexico border and to 50 km under the Great Plains (Olsen and others, 1979). North-south interface dips are small (0-2°) such that uplifted Moho beneath the rift exists from the southern border of New Mexico northward to Colorado. Discontinuous reflection segments on COCORP lines within the rift basin have two-way travel times that correspond well to a depth of 33 km (Brown and others, 1979).

(2) The sub-Moho compressional velocity (P_n velocity) beneath the rift axis is 7.6-7.7 km/s, significantly lower than velocity of "normal" mantle (8.0-8.2 km/s) beneath the Great Plains. Gravity modeling suggests that a low density layer which we presume correlates with this low P_n material persists westward from the rift beneath the Colorado Plateau at least as far as northeastern Arizona, where P_n has been directly measured at 7.8 km/s along the reversed Chinle-Hanksville line. Black and Braile (1982) argue that such low P_n values are primarily due to high temperatures in the mantle. Velocities of 7.6-7.9 km/s therefore strongly suggest that the asthenosphere is in direct contact with the base of the crust beneath the rift and southeastern

Colorado Plateau, without any intervening normal mantle or subcrustal lithosphere.

The very broad gravity low extending across the entire state at the latitude of Albuquerque (fig. 2) is related in part to the shape of the low velocity zone in the upper mantle (the asthenosphere). Other east-west gravity profiles between latitudes 32° and 38° also show this asthenospheric diapir, which thus forms a ridge-like Moho upwarp approximately parallel to the surface trace of the rift (Cordell, 1978; Ramberg and others, 1978). Both heat flow and electrical conductivity measurements support the gravity picture of an asthenospheric upwarp. The axis of the asthenospheric low does not coincide with the axis of the rift but instead is displaced about 200 km westward, approximately coincident with the continental divide (Ander, 1981).

(3) The compressional velocity in the lower crust beneath the rift (6.4-6.5 km/s) is substantially less than lower crustal velocities (6.7-6.8 km/s) under the flanks both to the east and west. Lower crustal velocities on the order of 6.5 km/s are rather uncommon in continental North America, existing mainly in the Great Basin section of the Basin and Range province and in the Rio Grande rift (Prodehl, 1979; Braile and others, 1984; written communication). We interpret such subnormal lower crustal velocities to be mainly due to high crustal temperatures and to suggest that no major compositional difference exists between the lower crust beneath the rift and that adjacent to it. The intermediate-wavelength gravity high (fig. 2) is often interpreted to indicate mafic igneous rocks intruded into the lower crust (an "axial dike" or, more properly composite batholith). However, in the Rio Grande rift the gravity signature can as well result from the equivalent replacement of lower density crustal rock with higher density mantle material because of the thinning of the lower crust. If there were a large intrusion

of mafic material, such as a dike swarm, in the lower crust, we would expect a very considerable increase in density and hence a corresponding increase in seismic velocity (to values of the order of 7.3-7.7 km/s) of the lower crust. In fact, the seismic results show a decrease in lower crustal seismic velocity compared to values in the flanks. Therefore, we do not consider the gravity high to be a persuasive argument for a large lower crustal mafic dike system but believe crustal thinning can account for almost the entire effect. The GNOME profile data (Stewart and Pakiser, 1962) also indicate a third (7.1 km/s), deeper layer beneath the usual 6.8 km/s lower crustal layer along the eastern New Mexico/west Texas border area. Such higher velocity deep layers are commonly observed in craton and platform areas in other parts of the world and possibly are related to evolution of older continental crust (for example, "underplating"). Another refraction line running eastward from GNOME (Romney and others, 1962) into central Texas was too sparsely instrumented to clearly show how far this bottom crustal layer may extend eastward.

(4) Unusually strong wide-angle reflections at precritical distances from refraction profiles in the southern Albuquerque basin imply the presence of a thin, tabular, low rigidity (that is, abnormally low S velocities) layer at midcrustal depth (about 20 km) in the vicinity of the Socorro "midcrustal magma body" (MCMB) (Olsen and others, 1982). The refraction observations suggest this anomalous sill-like layer probably surrounds but is more extensive than the partial melt or magma body between Socorro and Belen that has been extensively studied by reflection techniques and documented by Sanford and coworkers (Reinhart and others, 1979; Sanford and others, 1977). We tentatively correlate this feature with the boundary between the upper and lower crustal layers ("Conrad discontinuity,").

NATURE OF THE MOHO

Beneath the axis of the Rio Grande rift, existing seismic refraction data, mainly from the DICE THROW profile, indicate that the Moho is a sharp transition at the resolution of 1.0-1.5 km provided by the dominant 1 to 10-Hz frequencies characteristic of regional earthquake and explosion sources. On the other hand, the more restricted range COCORP-type deep reflection experiments, where dominant frequencies are in the 10 to 100-Hz range, reveal a more complex sandwich structure in the same region. Complex lamellae show considerable lateral variation, but the overall trend follows essentially the lower resolution "boundary" determined over much wider areas by refraction/wide-angle reflection experiments. Thus, the few-hundred-meter resolution reflection data indicate that the sub-rift Moho is a complicated structure which, in addition to being a major petrological and compositional change with depth, has had a complex metamorphic and horizontal stress history. The relatively small amplitudes of the P_n phase observed by reflection techniques along the Rio Grande rift axis indicate that the P-wave velocity in the asthenosphere actually decreases slightly with depth. Such decrease suggests that the sub-Moho temperature gradient is very small and that nearly isothermal conditions apply in the top few kilometers of the asthenospheric upwarp.

Because available refraction data for the adjacent Colorado Plateau and Great Plains are relatively sparse, with correspondingly more uncertain variations in amplitude-versus-distance behavior of the relevant seismic phases used in analysis, we cannot describe details of the Moho transition and sub-Moho properties with the same confidence as for the rift axis. However, by analogy with data from plateaus and shields in other parts of the world, we

expect some significant differences from what has been inferred for the central part of the rift.

NATURE OF THE CRUST

Our ideas concerning the nature of the upper crust and on mechanisms of crustal extension are greatly influenced by COCORP seismic reflection profiling in the Socorro area and southern part of the Albuquerque-Belen basin (Brown and others, 1979; 1980) and by observations of the Precambrian basement in New Mexico. Basically, we think that the upper and middle crust, and possibly the lower crust, are dominated by horizontal structures. COCORP data show a horizontally stratified upper crust with local transparent volumes (line 2A), which Brown and others (1979) suggest may be granitic plutons. Below about 10 km are numerous discontinuous, subhorizontal reflection segments varying in length, dip, density, and amplitude. Brown and others (1979) suggest this type of signature would be expected from a highly deformed metamorphic terrain with a dominant sub-horizontal fabric.

This interpretation fits well with our ideas concerning the structure of the upper crust, clues to which are present in the basement blocks surrounding the rift. The lithology and to a lesser extent the structure of the Precambrian basement of northern New Mexico is relatively well understood. Three major lithologic groups of Proterozoic age are exposed in the uplifted blocks of the central rift basin: volcanic and volcaniclastic rocks, quartzites and associated mature clastic sediments, and silicic plutonic bodies. With local exception, the volcanic sequence is oldest and is overlain structurally and perhaps stratigraphically by the quartzite sequence. Both sequences are intruded by younger batholithic to hypabyssal plutonic rocks. The sedimentary and volcanic rocks are folded into large (kilometers in

wavelength) overturned folds, the axial-plane foliations of which yield the seemingly pervasive structural fabric of the basement. This fabric strikes northwest to northeast, with local easterly trends, and dips at a high angle. However, the folds commonly plunge less than 50°, suggesting stratigraphic enveloping surfaces of rather low angle. The presence of a "low-angle" lithologic boundary is also suggested by regional aeromagnetic patterns, which show simple, broad, east-trending bands of contrasting magnetic intersity which correspond to outcrops of quartzite and metavolcanics (Zeitz and others, 1983).

Given the high-angle fabric so obvious at outcrop, it is tempting to characterize the basement as a mosaic of angular blocks separated by high-angle zones of structural weakness. Late Neogene high-angle rift faults tend to follow basement fabric and reinforce this view. However, structural analysis of the basement suggests that the earliest major deformation produced large-scale horizontal transport of the lithologic units, giving rise to nappes and overthrust sheets that were subsequently folded into the high-angle structures. Thus there was and is a pervasive low-angle fabric in the basement.

In extrapolating to the structure of the crust, the significance of Precambrian structure and lithology is the competence contrast produced by the juxtaposition of quartzite and volcanic terranes. At high levels in the crust, the quartzite is relatively brittle and contrasts strongly with the more incompetent metavolcanics and schists that surround it. Decollement and shear along stratigraphic boundaries are normal features of these terranes. Projecting into the upper crust, it is likely that strong layer contrasts will be found in the upper 5-10 km, and that horizontal fabrics will dominate where ductility contrasts along lithologic and structural boundaries are well

developed. Perhaps the high-angle fabric exposed in the uplifted blocks is a manifestation of upper-plate folding above a delamination surface of Proterozoic age. As previously noted, seismic reflection data support the suggestion of low-angle lithologic contrasts in the deeper parts of the upper crust.

Strong evidence of a dominant horizontal structure in the middle crust within the rift, corresponding essentially to the Conrad discontinuity, comes collectively from: (1) unusual S-to-S-wave reflections from the horizontal interface from microearthquakes that overlie the reflector; (2) strong P-to P-wave reflections from near vertical incidence COCORP profiling; and (3) unusually strong wide-angle reflections on refraction profiles that can best be explained in terms of an anomalously low S-wave velocity in the material just beneath the reflector interface (Olsen and others, 1982). Combined evidence from these various seismic techniques, plus supporting evidence from electrical, geodetic leveling, and heat flow measurements have lead to a widely accepted interpretation that this anomaly is due to a thin, sill-like magma body or partial melt layer at midcrustal depths (18-20 km) in the center of the rift. This mid-crustal magma body is most strikingly manifested beneath a 1700 km^2 area extending from Socorro northward almost to Belen (Sanford and others, 1977; Rinehart and others, 1979). Within this "central" region, Brocher (1981) has summarized the evidence indicating the total thickness of this magma body is of the order of only 1 km and consists of a highly complex, laminated series of sills of various degrees of fluidity and lateral "interfingering." Beyond the 1700 km^2 central region, the wide-angle data (Olsen and others, 1979; 1982) imply that the horizontal tabular geometry continues outward but that the seismic velocity anomaly is confined almost entirely to subnormal S-wave velocities. Velocities for P-waves are almost

indistinguishable from those in surrounding rocks at the depth ranges. This low resistivity aureole zone suggests a metamorphic reaction zone surrounding the central mid-crustal sill complex. A surprising and not well understood property of the magma body is its very horizontal upper surface, which is "flat" within the limits of resolution (±0.5 km) of the seismic techniques.

Although nearly all of the quantitative evidence for contemporary magma within the magma body comes from the intensively observed Socorro-to-southern-Albuquerque section of the rift and its eastern flank, similar, but more sparse and therefore less conclusive, geophysical observations suggest the midcrustal anomalous layer may extend intermittently along the rift and/or into the flank regions. For example, Hermance and Pedersen (1980) argue that magnetotelluric electrical conductivity data also favor a contiguous set of tabular units with a common generic origin along the rift. The midcrustal layer is undoubtedly not a continuous lithologic or petrological unit throughout, and — although the volume of magma is small in comparison with volumes of intrusives and volcanics in, say, the Kenya rift — the layer undoubtedly plays a very important but little understood role in the style of Rio Grande rift volcanism. Thus, we have projected some of the features of the Socorro magma body into our generalized cross section (fig. 2) in order to emphasize our perception of its importance, even though the specific illustrated section is about 100 km north of the best existing data.

In the middle crust, but still within the seismic upper crustal layer (fig. 2) is a transition from brittle to ductile behavior. The best evidence for the depth of this transition in the Rio Grande rift region is provided by the distribution of earthquake hypocenters. Although there is lower precision in measurements of hypocentral depths than for horizontal coordinates (epicenters), almost all regional earthquakes recorded since 1960 are from

depths less than 20 km and most are probably from shallower than 10-15 km (Sanford and others, 1979; 1981; Olsen, 1980). At strain rates applicable to crustal extension processes for the rift and Basin and Range provinces, the level of the brittle-ductile transition zone is probably at depths where temperatures are in the range 350°C - 500°C. In some localized high heat flow regions, such as beneath the young (1.1 - 1.4 m.y. old) calderas of the Jemez Mountains, the brittle-ductile transition comes within only a few km of the surface and large coincident aseismic areas exist. Focal mechanisms of the shallow crustal earthquakes are consistent with E-W tensional forces. The only exception to the general shallow depths of regional earthquakes were two moderate (magnitude ~4) events which occurred in 1977 near the base of the crust northwest of Mount Taylor. It is speculated (Sanford and others, 1979) that these deep events may be related to magmatic processes of the Jemez Lineament/Mount Taylor system.

Curie points for crustal materials (~550°C) are very similar to the higher temperature range for the brittle-ductile transformation; therefore, buried structures infered by aeromagnetic data all exist within the brittle domain.

The nature of the lower crust — worldwide as well as in continental rifts — is considerably more uncertain, not only because of limits of seismic resolution, but also because it is not clear that there are enough tectonically exposed sections of the lower continental crust that give representative samples of the global variety of lower crustal conditions. However, there now seems to be a consensus (for example, Bott, 1982) that the lower continental crust consists predominantly of granulite facies metamorphic rocks having an intermediate bulk composition similar to andesite or diorite. Presence of water (and other volatiles) in the deep crust is of fundamental importance in

that it can greatly affect seismic and electrical conductivity properties, but definitive laboratory and field studies are so few that these questions are currently being actively debated (Shankland and Ander, 1983). There is little doubt that the dominantly metamorphic nature of the lower crust implies a highly complex structural grain that we at present can only acknowledge in general terms (Smithson, 1978). While we recognize these complexities in both the lower and upper crust, we have refrained from trying to "cartoon" these in Figure 2 because we do not want to have these misunderstood as specific proposed features in the Rio Grande rift.

As pointed out above, seismic refraction data show a lateral variation in lower crustal average P-wave velocity from about 6.7-6.8 km/s beneath the flanks to 6.4-6.5 km/s beneath the rift axis (fig. 2). In addition to chemical composition, several other factors, such as pressure, temperature, fluids, and anisotropy due to preferential alignment of certain minerals (usually olivine) or major cracks, can affect observed elastic wave velocities. P-wave velocities increase with increasing pressures, especially at shallow depths (upper crust) where cracks and voids are being closed. For compositions and pressures characteristic of the lower crust, laboratory measurements (Christensen and Fountain, 1975; Christensen, 1979) indicate the pressure derivatives of wave velocities are small enough so that P- and S-velocities should not be increased by more than a bout 0.1 and 0.05 km/s, respectively, throughout the 20- to 40-km depth range. Temperature coefficients are negative, however, and Christensen's (1979) measurement of various granulites showed $-(\partial V/\partial T)_p$ is in the range of 0.5-0.7 x 10^{-3} km/s/°C at approximate lower crustal pressure conditions. Interpretations of the differences in the geotherms between the axial region of the rift and the flanks beneath the Great Plains and (more certainly) the Colorado Plateau

indicate the flank-rift temperature difference in the lower crust may be about 300°C at ~20 km depths and more than 400°C at the 30 to 35-km level. Thus, granulite temperature coefficients plus high sub rift heat flows are sufficient to decrease lower crustal P-velocities from the observed values of ~6.7 km/s in the flanks to 6.4-6.5 km/s beneath the rift without requiring any substantial changes in chemical composition between the two regions, although a decrease in density due to significant underplating by silicic magma such as might have resulted from mid-Tertiary magmatism could also explain this velocity decrease. This result leads us to conclude that there is no persuasive evidence for a massive mafic intrusive complex or dike swarm ("axial dike") in the lower crust beneath the axis of the Rio Grande rift, as has sometimes been postulated (from gravity data only) for the Kenya rift (Olsen, 1983). Certainly, the asthenospheric bulge beneath the central rift will generate some (predominately vertical) magma feeder conduits and local dikes that must be the main source of high average temperatures in the lower crust. However, the volumes and masses of mantle mafic material intruded into the lower crust must be less than a few (possibly ten) percent. Otherwise, both the lower crustal density and averaged seismic velocities would be increased substantially beneath the rift contrary to observations. The possible composition of the lower crust beneath the axis of the Rio Grande rift would be a fruitful problem for further modeling studies.

The process by which large amounts (50-200%) of crustal extension are produced has been concisely described by Hamilton (1982, 1983). Hamilton's model identifies three crustal layers, each with distinctive mechanical behavior: brittle fracturing and rotation in the upper crust, discontinuois ductile flow in the middle crust, and laminar ductile flow in the lower crust. The brittle-ductile transition is near the top of the middle crustal layer. A

significant feature of this model is the lenticular, transposed nature of the middle crust (see Callender, 1983, fig. 2), with lenses of more competent rocks ("megaboudins") interspersed with less competent material along ductile shear zones. We think this hypothesis adequately explains the crustal evolution of the Rio Grande rift and have cartooned this crustal structure in fig. 2.

As noted by Eaton (1982), the development of this type of crustal structure is strongly temperature and strain-rate dependent. In the Rio Grande rift, significant crustal extension is confined to the early Neogene (see next section), implying that the appropriate combination of high (convective?) heat flow, rapid strain rate, and resulting upward mass transport must have existed only at this time. Subsequently the rift must have experienced a decrease in strain rate and upward mass transport (both plastic flow and magmatic upwelling) in a manner similar to that described by Eaton for the Basin and Range province.

Magmatic transport paths through a crust altered by significant extension is presumably complicated. In the upper crust, brittle fracturing to depths of 10 km would allow relatively steep near-surface conduits to develop, and would result in the aligned volcanic centers which are commonly observed in the late Neogene volcanic fields of the rift. However, middle crustal structure would be lensoid and horizontally stratified, and the contact between middle and upper crust would probably be characterized by a low-angle detachment surface. This crustal environment might yield magma "pillows" and stratiform, sill-like intrusions in the middle crust, such as the Socorro magma body. It would also produce strong seismic reflectors near the brittle-ductile transition.

STRUCTURAL DEVELOPMENT

We must keep in mind that the picture of the Rio Grande rift presented to this point is simply a "snapshot" of an evolutionary process. Features of all ages, including those inherited from the pre-rift history, are superimposed. To understand the rifting process, we must understand structural and magmatic developments of the rift as a function of time.

The geometry of rift-basins and Neogene high-angle faults in the Rio Grande rift has been characterized by numerous authors (e.g., Chapin, 1971; Chapin and Seager, 1975; Cordell, 1978; Seager and Morgan, 1979). Until recently, the generally accepted model of rift geometry was a commonly asymmetric, graben-like zone bounded by high-angle normal faults (e.g., Chapin, 1971; Woodward and others, 1975; Brown and others, 1980). These faults were thought by some to listrically shallow near the brittle-ductile transition (e.g., Woodward, 1977). Commercial seismic reflection profiling in the rift (L. Russell, 1981, personal communication), reinterpretation of the COCORP deep seismic reflection profile (Cape and others, 1982), and recent structural analyses of rift-bounding faults (e.g., Seager, 1981; Chamberlin, 1983a; Lipman, 1983, Rhoades and Callender, 1983) now suggest this model is inaccurate or incomplete.

Instead, there appears to be a significant component of low-angle faulting in the Rio Grande rift. It is unclear whether low-angle faulting in the Rio Grande rift involves domino-style movement (Morton and Black, 1975; Chamberlin, 1983a), listric faulting (Cape and others, 1982), regional crustal shear (Wernicke and Burchfiel, 1982; Bird, 1979), detachment faulting (Frost and Martin, 1982; Callender and Zilinski, 1976; Rhoades and Callender, 1983), or some combination of the above models.

Figure 3 presents published examples of Neogene low-angle faults in the Rio Grande rift. The north end of the Sandia uplift (fig. 3a) plunges approximately 20°N. In down-plunge projection, the map of Kelley (1977) shows the San Francisco-Placitas fault zone to be a listric fault, dipping west (L. Russell, personal communication, 1981). Seismic reflection profiling in the Albuquerque basin west of the Sandia uplift supports this interpretation (L. Russell, personal communication, 1982). In addition, recent work in the Placitas area confirms low-angle, northwest-dipping faults and shears within the Paleozoic section and at or near the Phanerozoic-Precambrian contact (J. Callender, unpublished data). Rhoades and Callender (1983) described similar low-angle structures along the west side of the Sandia uplift, 10-20 km south of Placitas. In all cases, late Neogene high-angle normal faults truncate the low-angle structures.

Figure 3b shows the low-angle Carrizo fault of early Neogene age (Callender and Zilinski, 1976) along the western edge of the Albuquerque basin. The Carrizo fault is intruded by early Neogene intermediate and mafic hypabyssal rocks, suggesting the fault zone acted as a conduit for local magmatism. Similar structures have been described in the Joyita Hills on the eastern edge of the Socorro basin, 60 km southeast (Rosen, 1983; Osburn and Eggleston, 1983; Smith, 1983). These low-angle faults are confined to the Phanerozoic section and are commonly associated with large ductility contrasts between stratigraphic units. The low angle faults in the Lucero uplift and Joyita Hills are truncated by late Neogene high-angle normal faults.

One of the most carefully studied areas of low-angle faulting in the Rio Grande rift is the Lemitar Range near Socorro (fig. 3c). Chamberlin (1983a) suggested early Neogene extension of about 200% along domino-style faults in

this area. Late Neogene high-angle faulting and block-tilting are superimposed on this earlier deformation. Chamberlin noted that accelerated periods of domino-style faulting were contemporaneous with silicic volcanism, particularly in the early Neogene (31-20 million years ago).

The Jeter fault in the Ladron Mountains (fig. 3d), one of the first low-angle faults to be described in the Rio Grande rift (Black, 1964), has been characterized as a thrust fault (Black, 1964), low-angle normal fault (Kelley, 1977), domino-style fault (Chamberlin, 1983b), or detachment zone (T. Shackleford, personal communication, 1982). It shows many of the characteristics of a regional upper plate detachment surface (K. Gillespie-Nimick, M.S. thesis, in progress), including intense brittle deformation in both sedimentary and Precambrian crystalline rocks. It is truncated by late Neogene high-angle normal faults and is commonly the locus for metallic mineralization.

Similar low-angle structures exist in the southern part of the Rio Grande rift (fig. 3e-h). With the exception of the Franklin Mountains (fig. 3h), Neogene low-angle faults are clearly cut by late Neogene high-angle normal faults. In the Franklin Mountains, the age of low-angle faulting is uncertain, but comparison with the carefully studied Organ Mountains to the north (Seager, 1981) suggests that these faults are similar in style and age to early Neogene low-angle faults in the Organ Mountains.

Additional low-angle structures have been described in the northern Rio Grande rift (e.g., Spiegel and Baldwin, 1963; Lipman, 1983; Muehlberger, 1979). As studies of intrabasin and basin-margin uplifts continue, undoubtedly many more such features will be found.

Thus, Neogene low-angle faults are not uncommon features of the Rio Grande rift. They predate the high-angle normal faults of late Neogene age

and suggest a major shift in structural style and mode of crustal extension with time. The low-angle structures seem to be temporally associated with intense intermediate to silicic volcanic activity in southwestern New Mexico, which culminated in early Neogene time. Abnormal early Neogene crustal heat flow may have precipitated significant high-level crustal stretching along low-angle structures. This may have been accomplished by the rise of the brittle-ductile transition in the upper crust. Convective heat transfer, by massiv intrusion of silicic magmas into the continental crust in the middle Tertiary (Elston, 1984), may have provided the thermal input to allow this stretching.

Hence, the structural development of the rift apparently occurred during two discrete time intervals, an early phase characterized by low angle faults, and a later phase dominated by high-angle normal faults. Low-angle faults are also typical of the early phases of crustal extension in the nearby Basin and Range province, in contrast to later deformation in the same area (Eaton, 1982; Frost and Martin, 1982). The similarities in style of deformation between the rift and the Basin and Range further illustrate that both regions are manifestations of the same event.

Furthermore, possible widespread low-angle faulting early in formation of the rift has major implications for the total amount of extension. All models of low-angle faulting demand a signficant amount of crustal stretching. Extension of more than 200% is possible with this geometry (Chamberlin, 1983a), whereas high-angle normal faulting yields extension of only 5-30% (Woodward, 1977).

VOLCANISM

Most of the volcanism associated with the Rio Grande rift, with some important exceptions such as the Jemez volcanic field (fig. 1), is basaltic and occurred less than 5 m.y. ago. [Volcanism in the Jemez field began more than 13 m.y. ago and includes enormous volumes of intermediate to silicic magmas (Smith and others, 1970; Gardner and Goff, this guidebook)]. These basalts consist of a variety of nepheline- and hypersthene-normative compositions which are generally similar to other late Cenozoic basaltic rocks of the western U.S. However, the most voluminous of the late Miocene to Recent basaltic volcanic field, the Taos Plateau volcanic field, is compositionally unique. It consists dominantly of a distinctive, low-alkali tholeiitic magma (Servilleta Basalt) with lesser volumes of more alkaline (but still hypersthene-normative) magmas. Minor quantities of intermediate to silicic magmas represent melts formed by crystal fractionation processes and by melting of the lower crust. The Taos field apparently reflected a major thermal source which generated large quantities of magmas at or near the top of the mantle, and was beginning to involve the crust in a major way (Lipman and Mehnert, 1979; Basaltic Volcanism Study Project, 1981, p. 108-131; Moorbath and others, 1983; Dungan and others, this guidebook).

In the central and southern rift, Servilleta-type magmas were not erupted (except for minor quantities south of Mt. Taylor) and lavas are not dominantly of any single composition. Neither do their compositions correlate in any unique way with their tectonic setting. (Perhaps because so few volcanic rocks occur, their compositional complexity is the more obvious.) In the Cerros del Rio volcanic field near Santa Fe, the next most voluminous late Cenozoic basaltic field, a variety of compositions were erupted: high-alkali tholeiite, basaltic andesite, alkali olivine basalt and basanite (Baldridge,

1979). Farther south, both tholeiitic and alkaline magmas were erupted (Aoki and Kudo, 1976; Kelley and Kudo, 1978; Baldridge and others, 1982). East and west of the main rift graben (primarily along the Jemez lineament) volcanic fields include more alkaline compositions (nephelinites, basanites, mugearites) than occur within the rift but also range in composition to include high-alkali tholeiitic rocks that characterize much of the central rift. In the Lucero volcanic area, south of Mt. Taylor (fig. 1), minor volumes of Servilleta-type magmas occur (Baldridge and Perry, 1983).

H[illegible]no single composition is dominant along the rift; neither is there any e[illegible]n of composition with time nor unique correlation of composition with tectonic setting. In the Taos area, Lipman and Mehnert (1975) contrasted the Servilleta basalts to basalts outside the axial graben and proposed that the basalt compositions delineated the aesthenospheric upwarp. That is, tholeiitic basalts in the axial graben were derived from very shallow depths (near the base of the crust) at the top of the upwarp, whereas more alkaline basalts outside the grabens were derived from the flanks of the uplift at much greater depths. We do not disagree with this model for the Taos area. Certainly our lithospheric profile (fig. 2) is compatible with it. We emphasize however that the Servilleta basalts are compositionally unique compared to other basalts in the rift (and perhaps compared to other basalts of the Southwest?) and thus indicate that the Taos Plateau volcanic field represents a unique and localized heat source. Hence we do not generalize the petrogenetic model of Lipman and Mehnert (1975) to the rift as a whole. We think instead that the situation is much more complex. The compositions of volcanic rocks in the rift as a whole seem to indicate that basalts were generated at various levels in the asthenospheric upwelling, implying an unintegrated heat source with only local melting. The fact that volcanic

fields outside of the axial graben include compositions more alkaline than those inside suggests that magmas from deeper in the asthenosphere are erupted to the surface.

Most workers agree that, in addition to the post-5 m.y. pulse of volcanism, an early pulse also occurred (about 30-18 m.y. ago), coinciding generally with early structural development of the rift. These two magmatic events were separated by a mid-Miocene lull in volcanism (Chapin and Seager, 1975; Baldridge and others, 1980). We also agree with this picture of two separate magmatic pulses, but emphasize that this earlier event — as a rift-wide basaltic phenomenon — was extremely minor (fig. 4). Most of the generalizations that have been made regarding an early rift event are based on work in southwestern or southern New Mexico (e.g., Chapin and Seager, 1975; Cook and others, 1979; Seager et al., 1984). In this region, the enormous amount of mafic volcanism 30-18 m.y. ago was related not to rifting, but to (and was part of) the Mogollon-Datil volcanic field of dominantly intermediate to silicic magmas (fig. 4). This does not mean that rifting was not an immediate cause of at least some of this volcanism. The extensional tectonic environment that was part of the rifting event may have allowed magmas to escape to the surface whereas in the pre-rift environment magmas were not able to ascend. [Alternatively, these magmas may have been able to reach the surface only after the upper crustal batholiths had solidified such that they could be brittlely fractured (Eichelberger and Gooley, 1977)]. It does mean, however, that the heat source which generated these magmas was part of the previous (subduction-related?) event and not of rifting, in contrast to a model for the evolution of the southern Rio Grande rift presented by Cook and others (1979) in which a series of rifting-related thermal (i.e., magmatic events are postulated. This volcanic (and thermal) event obviously must have

affected the lithosphere and crust, introducing compositional changes. (Elston, 1984) and perhaps, through convective heat transfer (e.g., Spohn and Schubert, 1983) initiating the rise of the brittle-ductile transition in the crust. The distinction between a prior major thermal event and one specifically associated with rifting is important in recognizing thermal constraints on the rifting process.

Similarly, the frequently-made generalization that early rift volcanism is basaltic andesite derives almost entirely from this work in southern and southwestern New Mexico. Large volumes of these lavas are basaltic andesite related to the more silicic, calc-alkaline magmas. However, the compositions of magmatic rocks emplaced 30-18 m.y. ago north of Socorro range greatly, with no obvious temporal or spatial pattern (fig. 4). For example, olivine nephelinites erupted southwest and north of Santa Fe 19-25 m.y. ago (Baldridge and others, 1980) were derived from deeper than 50 km and possibly as deep as 90 km (Green, 1970a, b). Yet in the same general area, quartz-normative tholeiitic basalts, derived from much shallower levels in the mantle, were erupted approximately contemporaneously. This lack of a temporal pattern in magma composition confounds attempts to construct simple models of diapir growth beneath the Rio Grande rift, as for instance was done by Wendlandt and Morgan (1982) for the East African rift. Instead, the data seem to require a very unintegrated heat source beneath the rift with only highly localized melting.

A striking feature of magmatism associated with the Rio Grande rift is the virtual absence of volcanic rocks — of any age — in the rift. The largest fields within the rift grabens (Jemez and Taos Plateau volcanic fields) are part of the northwest-trending Jemez lineament (fig. 1). The rest of the rift is generally devoid of volcanic rocks. An essential question is, then,

whether the lack of volcanic rocks in the rift is due to the fact that magmas were never generated, or that they were never able to penetrate the crust and erupt on the surface? Based on evidence (largely seismic) presented above, we see no reason to think that large quantities of rifting-related magma were ever generated. If this conclusion is correct, it has enormous consequences for the magnitude of the thermal event accompanying rifting. For example, it would imply that no major heat source is associated with the rifting event and that little or no deep upwelling occurred beneath the rift. This conclusion is compatible with the diverse compositions of volcanic rocks in the rift.

LITHOSPHERIC PROCESSES

The goal of our studies is an understanding of the processes of rifting: what drives the lithospheric system, and what are the ramifications of rifting on the crust and mantle. Much discussion of rifting is cast into the simplified concepts of "active" and "passive" (e.g., Basaltic Volcanism Study Project, p. 842-844). Certainly, our interpretation of the volcanic signature of the Rio Grande rift does not lead us to think that it is in any sense "active" (fig. 5a). There are neither large volumes of volcanic rocks (of any age) in the rift, nor are there convincing arguments for large quantities of magmatic rocks at depth. Thus, though significant crust thinning has occurred during rifting, this thinning has apparently been accomplished with little addition of heat into the system during the rift process. Modern, relatively high heat flow in the Rio Grande rift may be related to conductive heat transfer from the Early Tertiary thermal episode, with the delay time dependent on crustal thickness, rather than a significant syn-rift magmatic event.

Pre-rift, subduction-related(?) volcanism, however, may have substantially changed the mechanical and lithologic character of the lithosphere and crust, providing an important component of convective heat transfer into the crust and uplifting isotherms and the brittle-ductile transition. Rifting, particularly when low-angle faulting and large amounts of local crustal extension are involved in the upper crust, probably requires significant heat flow into the crust. Thus formation of the Rio Grande rift may have resulted from the (fortuitous?) combination of a thermally weakened lithosphere with a superimposed tensional stress regime. Early Tertiary convective heat flow may have been critical in softening the crust and allowing it to yield.

Our lithospheric profile (fig. 2) contain information that may pertain to mechanisms of rifting. One particular model (fig. 5b) for purely passive rifting (Turcotte and Emerman, 1983) postulates an asthenospheric "mushroom" geometry, in which asthenosphere is floored by subcrustal lithosphere with a probable compressional seismic velocity of about 8.0 km/s. As noted below, the axial seismic refraction lines along the Rio Grande rift do not seem to support the mushroom or floored "pillow" picture, perhaps because existing refraction lines "just happen" to overlie the "broken window" in the subcrustal lithosphere. Additional profiles in the near flanks might possibly reveal such structures. We feel, however, the existing deep seismic and gravity interpretations of the Rio Grande rift are much more in accordance with the broad domed picture of Figure 5a than to the mushroom concept. Preliminary interpretation of teleseismic delays by Davis and others (this guidebook) suggests the asthenospheric low-velocity "upwarp" anomaly broadens with depth and may extend to depths of 200 km or deeper beneath the rift in northern New Mexico and southern Colorado. There is, however, an important difference from the model of Figure 5a in that the Rio Grande system is very

asymmetric with uppermantle/asthenospheric anomalies extending westward under the Colorado Plateau (Ander, 1981).

Thus, the concepts of active and passive rifting are obviously highly oversimplified, and probably neither is directly relevent to the Rio Grande rift. A most important feature of the rift is that it is superimposed on a region which underwent a long and complex history of deformation and heating prior to rifting. In order to understand the rifting process, it is imperative to sort out phenomena uniquely associated with rifting (i.e., with crustal extension and lithospheric thinning) from those inherited from previous events. We do not see convincing evidence for major active deep lithospheric involvement during rifting. Instead, the discontinuous nature of rifting and the fact that the rift is part of a very broad region of deformation suggest that plate processes exert a dominant control on the formation and evolution of the Rio Grande rift. As we have stated above, however, this does not imply that the major thermal and magmatic event preceding rifting did not influence — or even perhaps control — the initiation of rifting.

The significance of the Rio Grande rift to the evolution of the continental lithosphere is illustrated by contrasting it to other rifts. Based on gravity modeling and several axial and crossing seismic profiles, Mooney and others (1983) derived a crustal model for the northern Mississippi Embayment (fig. 5c). This area is the site of a buried Late Precambrian rift that was reactivated in the Mesozoic. Mooney and others (1983) note the presence of the 7.3-km/s "domed" layer, which implies the lower crust in the rift vicinity has been altered by injection of mantle material. Mooney and others suggest such a "high-to-intermediate" velocity intrusion or lower crustal alteration may be a ubiquitous feature of continental rifts. A somewhat similar "pillow" feature has been inferred beneath the central region

of the Rhinegraben (fig. 5d), except there the rift pillow takes the form of a 5-km-thick velocity gradient zone between 6.4 and 8.0 km/s rather than a more uniform 7.2 to 7.4-km/s layer. In the flanks outside the Rhinegraben, the Moho returns to a first order discontinuity.

Although there is evidence for a 7.2-km/s deep crustal layer under the Great Plains (fig. 2), axial profile data within the Rio Grande rift and even to the west (DICE THROW, GASBUGGY, and Chinle-Hanksville) do not support the interpretation of such a floored, high-intermediate velocity layer above an approximately 8-km/s mantle. We have made synthetic seismograms for floored models and compared them to DICE THROW data where P_n (at a velocity of 7.6 km/s) can be clearly observed as a first arrival between ranges of 150 km and 350 km. If there were an 8-km/s "floor" at depths 5-15 km beneath the observed (33-km depth) 6.4-7.7 km/s transition, 8 km/s apparent velocity head-waves and wide-angle reflections from the floor layer would be very strong and would severely mask the observed 7.6 km/s P_n phase and associated wide-angle reflections. Although the Mississippi Embayment evidence for a floored structure is good, it is based predominantly on secondary arrivals of reflections at ranges less than 150 km and not on P_n first arrivals.

At present, the origin of the deep, approximately 7.2 km/s layer that appears to be found in some rifts is not well understood. This layer may represent lower crust that has been "densified" by intrusion of basaltic material. If so, perhaps the layer is present only in thermally active rifts such as the East African, or only in mature rifts, as its presence in the fossil Mississippi Embayment might suggest. The Rhinegraben may represent an intermediate evolutionary stage between a fossil system and a currently dynamic system such as the Rio Grande rift. We feel this idea is supported by

arguments of Black and Braile (1982) that P_n velocity values are dominantly determined by temperature.

An intriguing variant in the deep crust-mantle interactions that may help account for the asymmetry of the Rio Grande rift/Colorado Plateau system is Bird's (1979) suggestion of continental delamination (fig. 5e). The lower continental (subcrustal) lithosphere is in unstable mechanical equilibrium because it is denser than the underlying asthenosphere. If some process, such as fault breakage throughout the subcrustal lithosphere or plume erosion in the vicinity of the present rift, provided a line of weakness and an elongated conduit connecting asthenosphere with the base of the crust, the denser subcrustal lithosphere boundary layer could peel away and sink into the chemically equivalent but hotter and less viscous asthenosphere. Observed moderately low P_n velocities of 7.8 km/s extending from the rift westward under the Colorado Plateau (fig. 2) strongly suggest the existence of hotter asthenospheric material in contact with base of the crust, perhaps as far westward as the Arizona-New Mexico border. Bird (1979) suggests several possible geological and petrological consequences of this model that need to be explored in greater detail in connection with rift evolution.

Another property of the deep crust subcrustal lithosphere-asthenosphere complex that has potentially great impact on understanding lithospheric evolution and particularly rifting processes is P_n velocity anisotropy, which has been observed under the eastern flanks of the Rhinegraben (references in Olsen, 1983). In principle, P-wave anisotropy (and the associated but more difficult to observe S-wave birefringence and polarization) is capable of partially resolving ductile flow patterns and stress histories in the deep crust and the lithosphere/asthenosphere beneath the Moho. Because existing deep refraction coverage in the Rio Grande rift vicinity is so sparse, any

discussion at present has to be speculative and in the nature of hypothesis formulation for testing by experiments. Clearly, there are a wide variety of puzzles concerning basic rifting processes, both past and present, which require extensive deep seismic sounding observations over a large area for their definition and solution.

SUMMARY AND CONCLUSIONS

Rifting is a long-term process involving changes in the entire lithosphere. Manifestations in the crust of the rifting process are a relatively surficial part of a deeper process. It is therefore important to focus research attention on the subcrustal phenomena of rifting.

The evolution of the Rio Grande rift does not fit either simple active or passive models. For example, no compelling evidence exists for a major thermal event associated with rifting. yet heat — inherited from the immediately — preceding deformation regime — was a critical factor in, and may have been a necessary condition for, rifting.

Even though volcanism and extension associated with the Rio Grande rift are relatively minor, nonetheless the lithosphere beneath the rift is being permanently altered. Probably, for example, compositional changes in the lithosphere are leading to a density increase. The effect of rifting will probably not be continental splitting. Rather, we suspect that the lithospheric anomaly associated with the Rio Grande rift will ultimately lead to major basin formation.

ACKNOWLEDGMENTS

Preparation of this manuscript was supported by the Office of Basic Energy Sciences of the U.S. Department of Energy and by National Science Foundation grant EAR-8018506.

REFERENCES

Ander, M. E., 1981, Geophysical study of the crust and upper mantle beneath the central Rio Grande rift and adjacent Great Plains and Colorado Plateau: Los Alamos National Laboratory Report LA-8676-T, 218 p.

Aoki, K., and Kudo, A. M., 1976, Major-element variations of late Cenozoic basalts of New Mexico: New Mexico Geological Society Special Publication 5, p. 82-88.

Baldridge, W. S., 1979, Petrology and petrogenesis of Plio-Pleistocene basaltic rocks from the central Rio Grande rift, New Mexico, and their relation to rift structure, in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 323-353.

Baldridge, W. S., Damon, P. E., Shafiqullah, M., and Bridwell, R. J., 1980, Evolution of the central Rio Grande rift, New Mexico: new potassium-argon ages: Earth and Planetary Science Letters, v. 51, 309-321.

Baldridge, W. S., Perry, F. V., and Gladney, E. S., 1982, Petrology and geochemistry of the Cat Hills volcanic field, central Rio Grande rift, New Mexico: Geological Society of America Bulletin, v. 93, p. 635-643.

Baldridge, W. S., Bartov, Y., and Kron, A., 1983, Geologic map of the Rio Grande rift and southeastern Colorado Plateau, New Mexico and Arizona, supplement to Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication.

Baldridge, W. S., and Perry, F. V., 1983, Spatial and temporal patterns of late Cenozoic basaltic volcanism of the central Rio Grande rift area [abs.]: EOS (Transactions of the American Geophysical Union), v. 64, p. 753.

Basaltic Volcanism Study Project, 1981, Basaltic volcanism on the terrestrial planets: New York, Pergamon Press, 1286 p.

Bird, P., 1979, Continental delamination and the Colorado Plateau: Journal of Geophysical Research, v. 84, p. 7561-7571.

Black, B. A., 1964, The geology of the northern and eastern parts of the Ladron Mountains, Socorro County, New Mexico [M.S. thesis], Albuquerque, University of New Mexico, 117 p.

Black, P. R., and Braile, L. W., 1982, P_n velocity and cooling of the continental lithosphere: Journal of Geophysical Research, v. 87, p. 10557-10568.

Bott, M. H. P., 1982, The Interior of the Earth (2nd ed.): New York, Elsevier, 404 p.

Broche , T. M., 1981, Geometry and physical properties of the Socorro, New Mexico, magma bodies: Journal of Geophysical Research, v. 86, p. 9420-9432.

Brown, L. D., Krumhansl, P. A., Chapin, C. E., and others, 1979, COCORP seismic reflection studies of the Rio Grande rif in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 169-184.

Brown, L. D., Chapin, C. E., Sanford, A. R., and others, 1980, Deep structure of the Rio Grande rift from seismic reflection profiling: Journal of Geophysical Research, v. 85, p. 5173-5189.

Callender, J., 1983, Transposition structures in Precambrian rocks of New Mexico: New Mexico Geological Society Guidebook, 34th Field Conference, p. 143-146.

Callender, J. F., and Zilinski, Jr., R. E., 1976, Kinematics of Tertiary and Quaternary deformation along the eastern edge of the Lucero uplift, central New Mexico: New Mexico Geological Society Special Publication 6, p. 53-61.

Cape, C. D., McGeary, S., and Thompson, G. A., 1983, Cenozoic normal faulting and the shallow structure of the Rio Grande rift near Socorro, New Mexico: Geological Society of America Bulletin, v. 94, p. 3-14.

Chamberlin, R. M., 1983a, Cenozoic domino-style crustal extension in the Lemitar Mountains, New Mexico: a summary: New Mexico Geological Society, 34th Field Conference, p. 111-118.

_____, 1983b, Stop 4 discussion in Second Day Road Log: New Mexico Geological Society Guidebook, 34th Field Conference, p. 51-53.

Chapin, C. E., 1971, The Rio Grande rift, part I: modifications and additions: New Mexico Geological Society Guidebook, 22nd Field Conference, p. 191-201.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas: New Mexico Geological Society Guidebook, 26th Field Conference, 297-321.

Christensen, N. I., 1979, Compressional wave velocities in rocks at high temperatures and pressures, critical thermal gradients, and crustal low velocity zones: Journal of Geophysical Research, v. 84, p. 6849-6857.

Cook, F. A., McCullar, D. B., Decker, E. R., and others, 1979, Crustal structure and evolution of the southern Rio Grande rift, in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 195-208.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geological Society Special Publication 6, p. 62-70.

Cordell, L., 1978, Regional geophysical setting of the Rio Grande rift: Geological Society of America Bulletin, v. 89, p. 1073-1090.

Cordell, L., Keller, G. R., and Hildenbrand, T. G., 1982, Bouguer gravity map of the Rio Grande rift, Colorado, New Mexico, and Texas: U.S. Geological Survey Map GP-949.

Eaton, G. P., 1982, The Basin and Range province: origin and tectonic significance: Annual Review of Earth and Planetary Sciences, v. 10, p. 409-440.

Eichelberger, J. C., and Gooley, R., 1977, Evolution of silicic magma chambers and their relationship to basaltic volcanism, in Heacock, J. C., ed., The Earth's Crust: its nature and physical properties: American Geophysical Union, Geophysical Monograph 20, p. 57-77.

Elston, W. E., 1984, Subduction of young oceanic lithosphere and extensional orogeny in southwestern North America during mid-Tertiary time: Tectonics, v. 3, p. 229-250.

Frost, E. G., and Martin, D. L., eds., 1982, Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, 608 p.

Green, D. H., 1970a, A review of experimental evidence on the origin of basaltic and nephelinitic magmas: Physics of the Earth and Planetary Interiors, v. 3, p. 221-235.

Green, D. H., 1970b, The origin of basaltic and nephelinitic magmas: Transactions of the Leicester Literary and Philosophical Society, v. 64, p. 28-54.

Hamilton, W., 1982, Structural evolution of the Big Maria Mountains, northeastern California, in Fros., E. G., and Martin, D. L., eds., Mesozoic-Cenozoic tectonic evolution of the Colorado River region, California, Arizona, and Nevada: San Diego, California, Cordilleran Publishers, p. 1-27.

Hermance, J. F., and Pedersen, J., 1980, Deep structure of the Rio Grande rift: A magnetotelluric interpretation: Journal of Geophysical Research, v. 85, p. 3899-3912.

Kautz, P. F., Ingersoll, R. V., Baldridge, and others, 1981, Geology of the Espinoso Formation (Oligocene), north-central New Mexico: Geological Society of America Bulletin, Part II, v. 92, p. 2318-2400.

Kay, R. W., and Kay, S. M., 1981, The nature of the lower continental crust: inferences from geophysics, surface geology, and crustal xenoliths: Reviews of Geophysics and Space Physics, v. 198, p. 271-298.

Kelley, V. C., 1977, Geology of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 33, 59 p.

Kelley, V. C., and Kudo, A. M., 1978, Volcanoes and related basalts of Albuquerque basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 156, 30 p.

Laughlin, A. W., Brookins, D. G., Damon, P. E., and others, 1979, Late Cenozoic volcanism of the central Jemez zone, Arizona-New Mexico: Isochron/West, No. 25, p. 5-8.

Laughlin, A. W., Aldrich, M. J., and Vaniman, D. T., 1983, Tectonic implications of mid-Tertiary dikes in west-central New Mexico: Geology, v. 11, p. 45-48

Lipman, P. W., 1983, The Miocene Questa caldera, northern New Mexico: relation to batholith emplacement and associated molybdenum mineralization, in The genesis of Rocky Mountain ore deposits: Changes with time and tectonics: Proceedings of the Denver region Exploration Geologists Symposium, p. 133-148.

Lipman, P. W., and Mehnert, H. H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains, Geological Society of America Memoir 144, 119-154.

Lipman, P. W., and Mehnert, H. H., 1979, The Taos Plateau volcanic field, northern Rio Grande rift, New Mexico, in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 289-311.

Massingill, G. L., 1977, Geology of Riley-Puertocito area, southeastern margin of the Colorado Plateau, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Open File Report 107.

Mooney, W. D., Andrews, M. C., Ginzburg, A., and others, 1983, Crustal structure of the northern Mississippi embayment and a comparison with other continental rift zones: Tectonophysics, v. 94, p. 327-348.

Moorbath, S., Dungan, M. A., Harmon, R. S., and others, 1983, Pb-, O-, and Sr-isotopic evidence for mantle and lower crustal involvement in the genesis of intermediate lavas of the Taos Plateau volcanic field (TPVF) [abs.]: EOS (American Gophysical Union Transactions), v. 64, p. 753.

Morton, W. H., and Black, R., 1975, Crustal attenuation in Afar, in Pilger, A., and Rosler, A., eds., Afar depression of Ethiopia: Inter-Union Commission on Geodynamics Scientific Report 14, p. 55-65.

Muehlberger, W. R., 1979, The Embudo fault between Pilar and Arroyo Hondo, New Mexico: an active intracontinental transform fault: New Mexico Geological Society Guidebook, 30th Field Conference, p. 77-82.

Mueller, S., 1977, A new model of the continental crust, in Heacock, J. C., ed., The earth's crust — its nature and physical properties: American Geophysical Union, Geophysical Monograph 20, p. 289-317.

NMGS Map, 1982, New Mexico Highway Geologic Map: New Mexico Geological Society.

Olsen, K. H., 1979, The seismicity of north-central New Mexico with particular reference to the Cerrillos earthquake of May 28, 1918: New Mexico Geological Society Guidebook 30, p. 65-75.

_____, 1983, The role of seismic refraction data for studies of the origin and evolution of continental rifts: Tectonophysics v. 94, p. 349-370.

Olsen, K. H., Keller, G. R., and Stewart, J. N., 1979, Crustal structure along the Rio Grande rift from seismic refraction profiles, in R. E. Riecker ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 127-144.

Olsen, K. H., Cash, D. J., and Stewart, J. N., 1982, Mapping the northern and eastern extent of the Socorro midcrustal magma body by wide-angle seismic reflections: New Mexico Geological Society Guidebook 33, p. 179-185.

Osburn, G. R., and Eggleston, T. L., 1983, Geologic map and cross sections of small area of southern Joyita Hills, Fig. 1-22.4a in First Day Road Log: New Mexico Geological Society Guidebook, 34th Field Conference, p. 10.

Prescott, W. H., Savage, I. C., and Kinoshita, W. T., 1979, Strain accumulation rates in the western United States between 1970 and 1978: Journal of Geophysical Research, v. 84, p. 5423-5435.

Prodehl, C., 1979, Crustal structure of the western United States: U.S. Geological Survey Professional Paper 1034.

Ramberg, I. B., Cook, F. A., and Smithson, S. B., 1978, Structure of the Rio Grande rift in southern New Mexico and West Texas based on gravity interpretation: Geological Society of America Bulletin, v. 89, p. 107-123.

Rinehart, E. J., Sanford, A. R., and Ward, R. M., 1979, Geographic extent and shape of an extensive magma body at midcrustal depths in the Rio Grande rift near Socorro, New Mexico, in Riecker, R. E. ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 237-249.

Roller, J. C., 1965, Crustal structure in the eastern Colorado Plateau province from seismic refraction measurements: Seismological Society of America Bulletin, v. 55, p. 107-119.

Romney, C., Brooks, B. G., Mansfield, R. H., and others, 1962, Travel times and amplitudes of principal body phases recorded from GNOME: Seismological Society of America Bulletin, v. 52, p. 1057-1074.

Rosen, S., 1983, Geologic map and cross section, Fig. 1-15.2b in First Day Road Log: New Mexico Geological Society Guidebook, 34th Field Conference, p. 8.

Sanford, A. R., Mott, R. P., Schuleski, P. J., and others, 1977, Geophysical evidence for a magma body in the crust in the vicinity of Socorro, New Mexico, in Heacock, J. G., ed., The Earth's Crust: its Nature and Physical Properties: American Geophysical Union, Geophysical Monograph 20, p. 385-403.

Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1979, Seismicity of the Rio Grande rift, in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, p. 145-168.

Sanford, A. R., Olsen, K. H., and Jaksha, L. H., 1981, Earthquakes in New Mexico, 1849-1977: New Mexico Bureau of Mines and Mineral Resources Circular 171, 20 p.

Seager, W. R., 1981, Geology of Organ Mountains and southern San Andres Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Memoir 36, 97 p.

Seager, W. R., and Morgan, P., 1979, Rio Grande rift in suthern New Mexico, West Texas, and northern Chihuahua: in Riecker, R. E., ed., Rio Grande rift: tectonics and magmatism: American Geophysical Union Special Publication, 87-106.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and others, 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande rift: Geological Society of American Bulletin, v. 95, p. 87-99.

Shankland, T. J., and Ander, M. E., 1983, Electrical conductivity, temperatures, and fluids in the lower crust: Journal of Geophysical Research, v. 88, p. 9475-9484.

Smith, C. T., 1983, Structural problems along the east side of the Socorro constriction, Rio Grande rift: New Mexico Geological Society Guidebook, 34th Field Conference, p. 103-109.

Smith, R. L., Bailey, R. A., and Ross, C. S., 1970, Geologic map of the Jemez Mountains: U.S. Geological Survey, Map No. I-571

Smithson, S. B., 1978, Modeling continental crust: structural and chemical constraints: Geophysical Research Letters, v. 5, p. 749-752.

Smithson, S. B., and Brown, S. K., 1977, A model for lower continental crust: Earth and Planetary Science Letters, v. 35, p. 134-144.

Smithson, S. B , Johnson, R. A., and Wong, Y. K., 1981, Mean crustal velocity: a critical parameter for interpreting crustal structure and crustal growth: Earth and Planetary Science Letters, v. 53, p. 323-332.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico: U.S. Geological Survey Water-Supply paper 1525, 258 p.

Spohn, T., and Schubert, G., 1983, Convective thinning of the lithosphere: a mechanism for rifting and mid-plate volcanism on Earth, Venus, and Mars: Tectonophysics, v. 94, p. 67-90.

Stewart, S. W., and Pakiser, L. C., 1962, Crustal structure in eastern New Mexico interpreted from the GNOME explosion: Bulletin Seismological Society of America Bulletin, v. 52, p. 1017-1030.

Sun, M., and Baldwin, B., 1958, Volcanic rocks of the Cienega area, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 54, 80 p.

Toppozada, T. R., and Sanford, A. R., 1976, Crustal structure in central New Mexico interpreted from the GASBUGGY explosion: Seismological Society of America Bulletin 66, p. 877-886.

Turcotte, D. L., and Emerman, S. H., 1983, Mechanisms of active and passive rifting: Tectonophysics, v. 94, p. 39-50.

Tweto, O., 1978, Tectonic map of the Rio Grande rift system in Colorado, in Hawley, J. W., ed., Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, Sheet 1.

Wendlandt, R. F., and Morgan, P., 1982, Lithospheric thinning associated with rifting in East Africa: Nature, v. 298, p. 734-736.

Wernicke, B., and Burchfiel, B. C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 105-115.

Woodward, L. A., 1977, Rate of crustal extension across the Rio Grande rift near Albuquerque, New Mexico: Geology, v. 5, p. 269-272.

Woodward, L. A., Callender, J. F., and Zilinski, R. E., 1975, Tectonic map of the Rio Grande rift, New Mexico: Geological Society of America Map MC-11.

Woodward, L. A., Callender, J. F., Seager, W. R., and others, 1978, Tectonic map of Rio Grande rift region in New Mexico, Chihuahua, and Texas, in Hawley, J. W., ed., Guidebook to Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources Circular 163, Sheet 2.

Zietz, I., 1982, Composite magnetic anomaly map of the United States, part A: conterminous United States: U.S. Geological Survey Map, 1:2,500,000.

DISCLAIMER

FIGURE CAPTIONS

Fig. 1 Generalized tectonic map of the Rio Grande rift. After Woodward and others (1978), Tweto (1978), NMGS Map (1982), Baldridge and others (1983), shows location of cross-section, Figure 2.

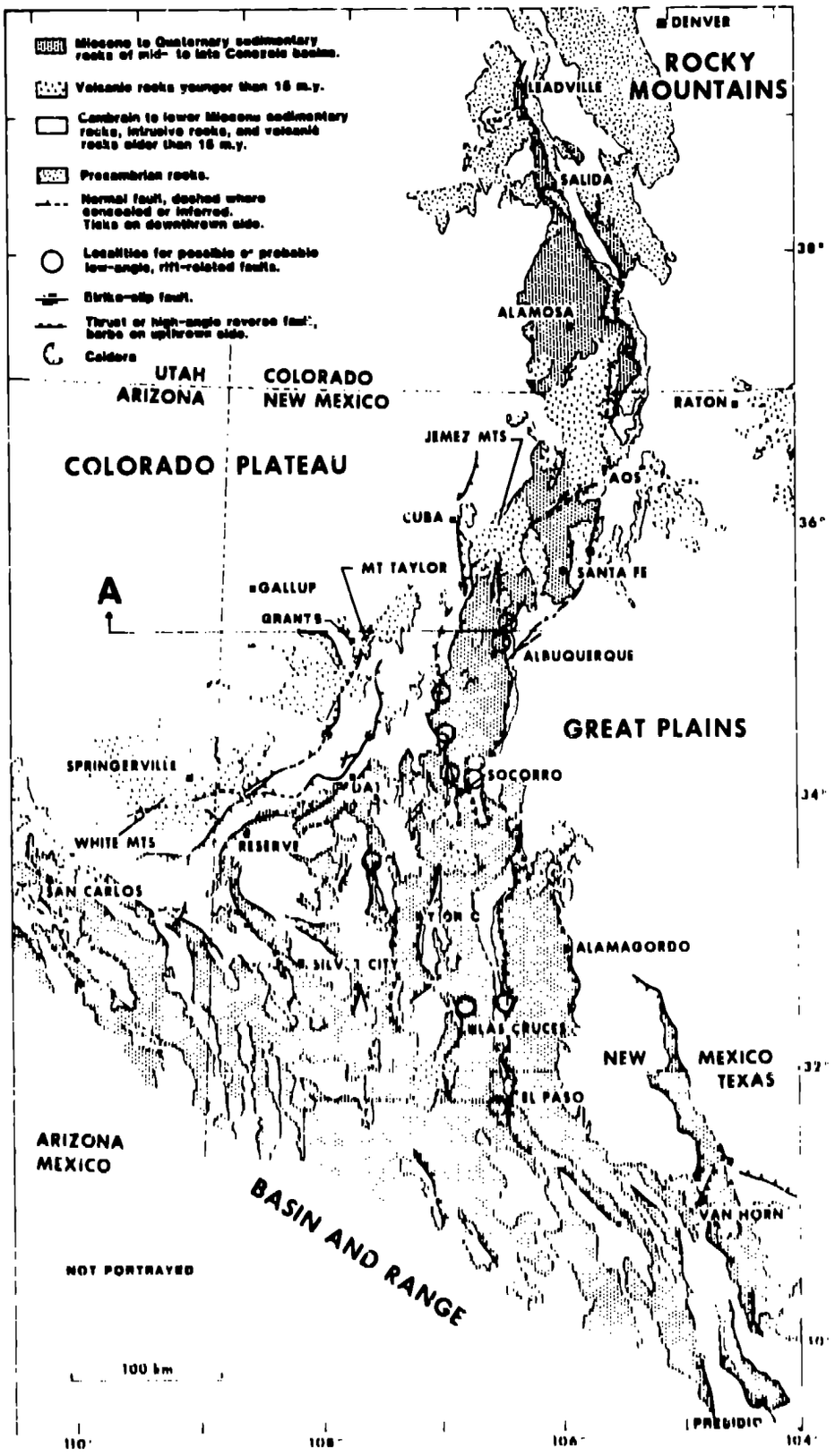
Fig. 2. Cross-section through northern Albuquerque-Belen basin. See Figure 1 for location. Locations of intracrustal boundaries interpreted from travel times and record sections of correlated phases are plotted as short, heavy lines at the longitudes where seismic profiles intersect the cross section. Profiles are identified by locations of the shotpoints (Chinle-Hanksville: Roller, 1965) or by code names of the main source explosions (DICE THROW: Olsen and others, 1979; GASBUGGY: Toppozada and Sanford, 1976; GNOME: Stewart and Pakiser, 1962). The Chinle, GASBUGGY, and GNOME profiles were obtained at a relatively early technological state in U.S. crustal profiling efforts, when station spacing was relatively coarse (10-50 km) and true amplitude/waveform data were inadequate to permit more than estimates of possible velocity gradients or fine structure in the principal crustal layers. DICE THROW average station spacing was about 3 km, allowing better gradient estimates using modern synthetic seismogram modeling techniques. Generalized distribution of earthquake hypocenters in the upper crustal layer is shown by asterisks, as are the specific deep crustal events of 1976/1977 (Sanford and others, 1979). A Bouguer gravity anomaly profile at the latitude of the cross-section is shown at the top (Cordell and others, 1982). The mid-crustal magma body at Socorro has been projected into the cross section.

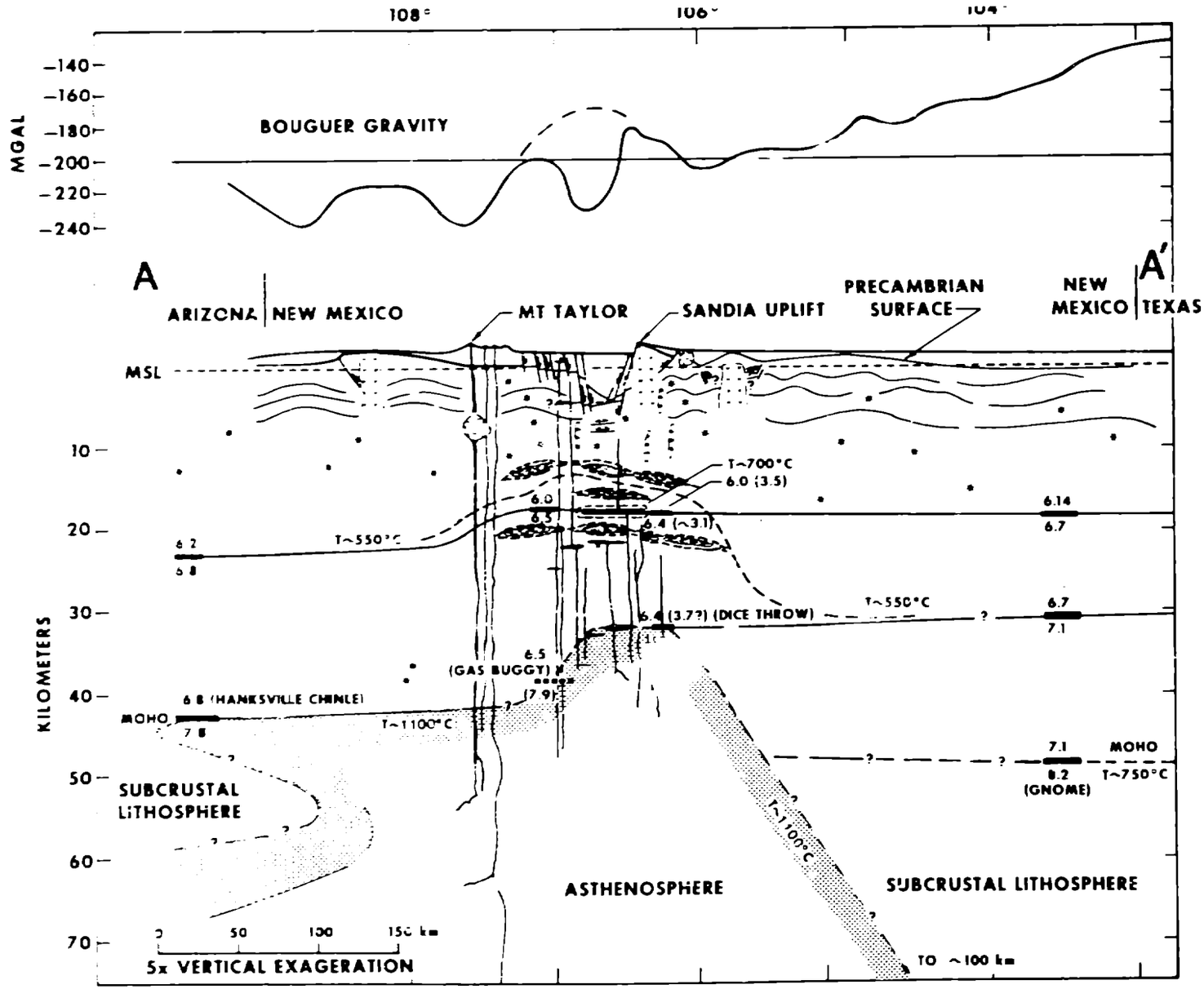
Fig. 3. Low-angle Neogene faults in the New Mexico part of the Rio Grande rift. See text for explanation. A. Map of northern Sandia uplift, after Kelley (1977); B. Cross-section through northern Lucero uplift, after

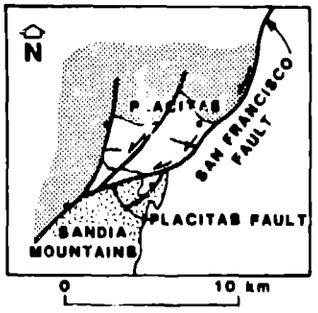
Callender and Zilinski (1976); C. Cross-section through Lemitar Mountains, after Chamberlin (1983a); D. Map and cross-section of Ladron Peak area, after Black (1964) and Chamberlin (1983b); E. Map of the Hillsboro area, after Kuellmer (1956); F. Cross-sections through San Diego Mountain (Tonuco uplift), after Seager and others (1971); G. Cross-sections through east side of Organ Mountains (4x vertical exaggeration), after Seager (1981); H. Cross-sections through northern Franklin Mountains, after Harbour (1972).

Fig. 4. Basaltic rocks inferred or known to have been emplaced between about 30 and 18 m.y. ago. Diagram differs considerably in degree of detail represented: North of about 34 virtually every data point and outcrop is plotted; south of this latitude, outcrops are generalized and most data points are not plotted. Much data exists, however, which indicates that these rocks are generally basaltic andesites. Broad dashed lines show areas of Oligocene to Miocene (age in m.y. ?), intermediate to silicic volcanism: M-D is Mogollon-Datil volcanic field, SB Sierra Blanca, O Ortiz, L Latir (including "early rift volcanic field" of Lipman and Mehnert, 1979). Data from Sun and Baldwin (1958), Callender and Zilinski (1976), Massingill (1977), Laughlin and others (1979, 1983), Lipman and Mehnert (1979), Baldridge and others (1980), Kautz and others (1981), NMGS Map (1982), Lipman (1983), Seager and others (1984), and Vaniman (unpublished data).

Fig. 5. Schematic cross sections of the Mississippi embayment and Rhinegraben and generalized models showing aspects of the rifting process.

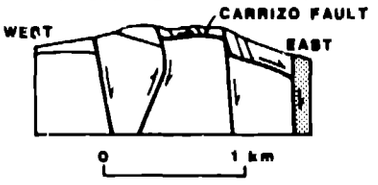

Miocene to Quaternary sedimentary rocks of mid- to late Cenozoic basins.
Volcanic rocks younger than 16 m.y.
Cambrain to lower Miocene sedimentary rocks, intrusive rocks, and volcanic rocks older than 16 m.y.
Precambrian rocks.
Normal fault, dashed where concealed or inferred. Ticks on downthrown side.
Localities for possible or probable low-angle, rift-related faults.
Strike-slip fault.
Thrust or high-angle reverse fault, barbs on upthrown side.
Caldera
DENVER
ROCKY MOUNTAINS
LEADVILLE
SALIDA
ALAMOSA
UTAH
ARIZONA
COLORADO
NEW MEXICO
RATON
JEMEZ MTS
COLORADO PLATEAU
AOS
CUBA
MT TAYLOR
SANTA FE
A
A'
GALLUP
GRANTS
ALBUQUERQUE
GREAT PLAINS
SPRINGERVILLE
SOCORRO
WHITE MTS
RESERVE
SAN CARLOS
ALAMAGORDO
LAS CRUCES
NEW MEXICO
TEXAS
EL PASO
ARIZONA
MEXICO
BASIN AND RANGE
VAN HORN
NOT PORTRAYED
100 km
PRESIDIO
110°
108°
106°
104°
38°
36°
34°
32°
30°


108°
106°
MGAL
-140
-160
-180
-200
-220
-240
BOUGUER GRAVITY
A
A'
ARIZONA | NEW MEXICO
MT TAYLOR
SANDIA UPLIFT
PRECAMBRIAN SURFACE
NEW MEXICO | TEXAS
MSL
KILOMETERS
10
20
30
40
50
60
70
T~700°C
6.0 (3.5)
6.14
6.7
6.2
6.8
T~550°C
6.4 (~3.1)
6.4 (3.7?) (DICE THROW)
T~550°C
6.7
7.1
6.5
(GAS BUGGY)
(7.9)
6.8 (HANKSVILLE CHINLE)
MOHO
7.8
T~1100°C
7.1
MOHO
8.2
(GNOME)
T~750°C
SUBCRUSTAL LITHOSPHERE
ASTHENOSPHERE
T~1100°C
SUBCRUSTAL LITHOSPHERE
TO ~100 km
0
50
100
150 km
5x VERTICAL EXAGERATION



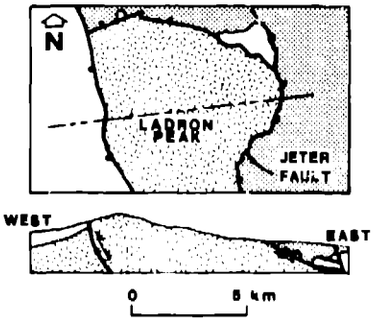
LUCERO UPLIFT

NO VERTICAL EXAGGERATION



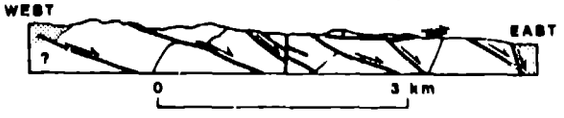
LADRON PEAK

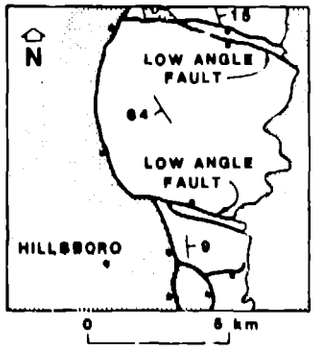
NO VERTICAL EXAGGERATION



LEMITAR MOUNTAINS

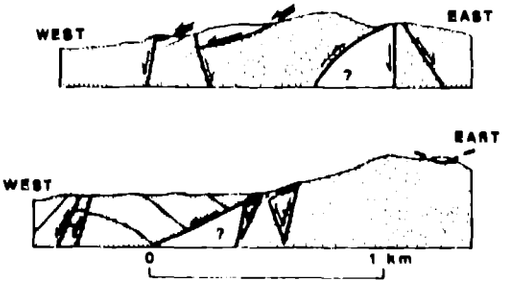
NO VERTICAL EXAGGERATION





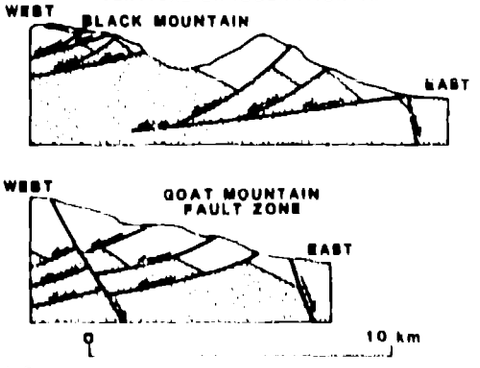
SAN DIEGO MOUNTAIN

NO VERTICAL EXAGGERATION



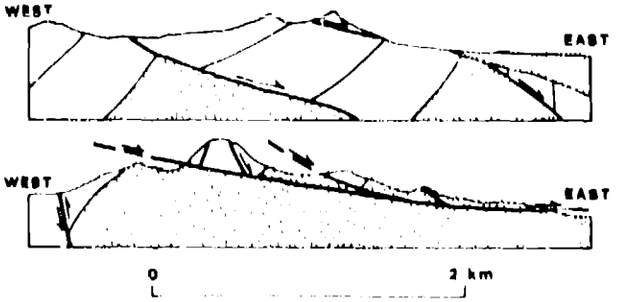
ORGAN MOUNTAINS

VERTICAL EXAGGERATION 4x



FRANKLIN MOUNTAINS

NO VERTICAL EXAGGERATION



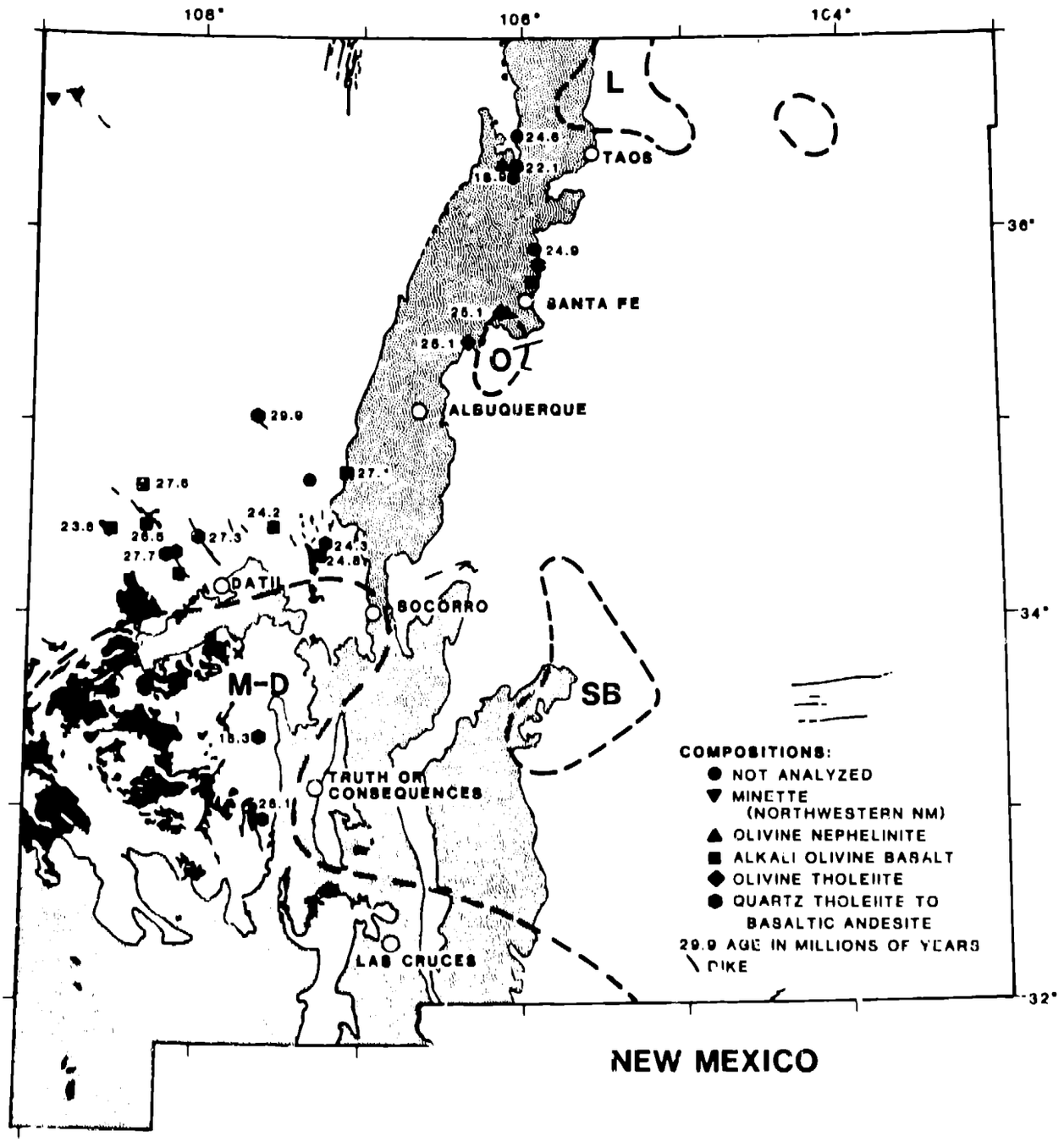
LATE TERTIARY SEDIMENTARY ROCKS

CAMBRIAN TO EARLY TERTIARY ROCKS

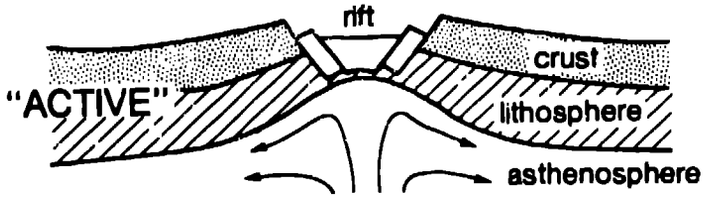
PRECAMBRIAN ROCKS

GROUND SURFACE OR BEDDING ON CROSS SECTION

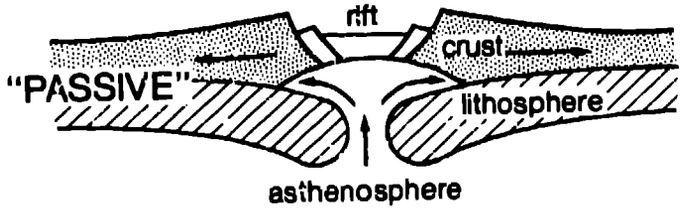
FAULT


108°
106°
104°
36°
34°
32°
L
TAOS
24.6
22.1
18.5
24.9
SANTA FE
28.1
26.1
OT
ALBUQUERQUE
29.9
27.6
27.4
24.2
23.8
26.6
27.3
24.3
27.7
24.8
DATIL
SOCORRO
M-D
SB
18.3
TRUTH OR CONSEQUENCES
28.1
LAS CRUCES
COMPOSITIONS:
NOT ANALYZED
MINETTE (NORTHWESTERN NM)
OLIVINE NEPHELINITE
ALKALI OLIVINE BASALT
OLIVINE THOLEIITE
QUARTZ THOLEIITE TO BASALTIC ANDESITE
29.9 AGE IN MILLIONS OF YEARS
DIKE
NEW MEXICO

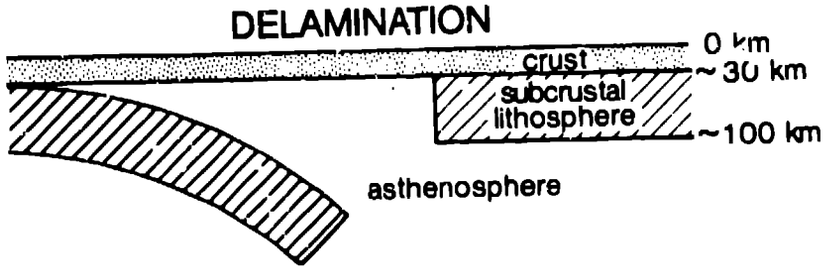
a)


rift
crust
"ACTIVE"
lithosphere
asthenosphere

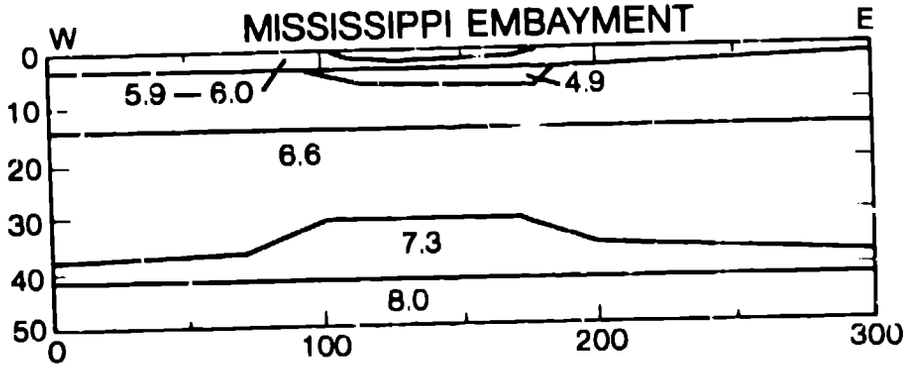
b)


rift
crust
"PASSIVE"
lithosphere
asthenosphere

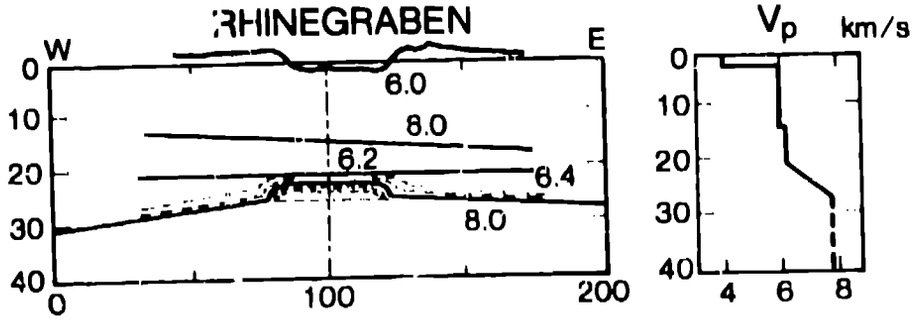
c)


DELAMINATION
0 km
crust
~30 km
subcrustal
lithosphere
~100 km
asthenosphere

d)


MISSISSIPPI EMBAYMENT
W
E
0
10
20
30
40
50
5.9 — 6.0
4.9
6.6
7.3
8.0
0
100
200
300

e)


RHINEGRABEN
W
E
0
10
20
30
40
6.0
6.0
6.2
6.4
8.0
0
100
200
Vp
km/s
0
10
20
30
40
4
6
8